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PLASMA METHODS OF ACCELERATION†

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In this paper theoretical and experimental investigations on methods of acceleration in plasma are presented; these investigations are based on the use of waves excited by electron beams in plasma waveguides. The following problems are treated: the increase in excitation effectiveness by intense relativistic beams of plasma waves essential to acceleration; the interaction of relativistic modulated beams with plasma, and others. The experiments made so far are shown to be in full agreement with theory.

At present two approaches in collective acceleration methods for charged particles have been established: acceleration by means of electron rings,[1] bunches and beams moving in vacuum, and acceleration by means of various types of waves which are excited in a plasma by intense relativistic and nonrelativistic beams and by external ultra-high-frequency sources as well. An important advantage of the vacuum methods lies in small concentration or absence of the ion component, as electrons moving in rings, bunches and beams relative to ions can give rise to strong streaming instabilities and associated anomalous diffusion, ion and electron heating and break-up of these systems. On the other hand, in implementation of the vacuum methods the problems of developing, forming and transporting such complex systems as rings and bunches are far from being simple, as are the problems of elimination of radiation instabilities and instabilities connected with moving of beam electrons relative to accelerated ions. With the current increase in rings and bunches necessary for the increase of accelerating field strength, the difficulties of confinement for noncompensated charges are increased, and therefore there is a necessity for a high increase of external confining fields, either partial or full compensation of the space charge, that is the transition to autostabilized Bennett–Budker beams or to acceleration in a plasma.

One of the plasma acceleration methods is the method of acceleration by means of waves which are excited in a plasma by intense relativistic and nonrelativistic beams and external sources of super-high-frequency electromagnetic fields.[2,3] ‡ The distinctive feature of this acceleration method lies in the fact that forces acting upon electrons to create an acceleration field are not constant in direction but oscillate. These forces are, therefore, equal to zero on the average in an oscillation period or spatial period of the order of the wavelength, and the equilibrium charge of electrons in the plasma is compensated and does not lead to acceleration. As in this case there is no need in external fields for confinement and stability of space charge, the maximum density of charge and, consequently, the maximum strength of an accelerating field can be increased appreciably. The maximum strength of ordinary wave electric field in plasma which is defined by the trajectory intersection condition is

$$E_{\max} \approx \sqrt{4\pi n_p mc^2}.$$

For plasma density between 10^{12} and 10^{16} cm^{-3} it reaches 0.1 to 10 GeV/m. The method under study allows for carrying out the transition to the quasi-continuous acceleration process, this giving the possibility for increasing the average current of accelerated particles. It is very important that in this case the very complex problem of providing

† A survey at the Symposium on Collective Methods of Acceleration, Dubna, 1972. The report is based on theoretical investigations made by V. D. Shapiro, V. I. Kurilko, S. S. Moiseev, V. I. Shevchenko, their collaborators and the author, and on experimental investigations carried out by A. K. Berezin, L. I. Bolotin, Yu. V. Tkatch, E. A. Kornilov, N. S. Pedenko, A. M. Egorov, their collaborators and the author.

‡ A number of interesting modifications with plasma and beam acceleration methods are examined in reports by M. S. Rabinovich and A. A. Kolomenskii.

longitudinal stability for moving electron bunches and rings is eliminated. For excitation of ordinary or single waves (pulses) in a plasma by means of electron beams the power of the excited oscillations is defined by the power of these beams and the effectiveness of beam energy transformation into wave energy. But it is by moving of electron beams in plasma due to compensation not only of their charges but also the currents, that the maximum current value and hence, the beam power is greatly increased. As was shown by theoretical studies of the nonlinear stage of beam-plasma collective interactions, from 10 to 45 per cent of the beam energy may be transferred to excite wave oscillations in plasma. Experimental investigations made at the Physical-Technical Institute of the Academy of the Ukrainian SSR in Kharkov with 10^7 and 10^9 watt beams confirmed these theoretical conclusions. In recent experiments with beams whose energy is 10^{10} to 10^{11} watts, such high effectiveness has not yet been reached; however, there is serious reason to suppose that, with proper modification of machines and changes in experimental conditions, the part of energy spent on wave excitation would comprise 20 to 30 per cent. In this case the excitation problem of waves necessary for acceleration may be considered as a settled one, as the strengths of accelerating fields will already constitute 10^6 to 10^7 V/cm and with beam energy of 10^{12} to 10^{13} watts they will be 10^7 to 10^8 V/cm.

Over a long period of time the existence of fields in plasma of the order of tens, hundreds and millions of volts/centimeters was questionable. As was shown in experiments by Graybill and Nablo[4] and in subsequent papers, the strength of fields which accelerate ions already mounts up to 0.5 to 0.6 MV/cm. It is true, this strength was obtained over a distance of only 5 to 6 cm. In work at the Physical-Technical Institute field strengths of tens of keV were obtained over distances of 100 to 150 cm. Thus, the existence of high-strength fields in plasma is no longer in doubt. The main forward step consists in a substantial increase of acceleration length and elimination of nonregular nature of acceleration processes.[5] Toward solution of the last problem there has been substantial progress in plasma-beam systems at lower currents; these methods are likely to be fully transferred to high currents as well. For fuller realization of the advantages of the plasma method it is necessary to overcome still more inherent difficulties which are associated with the development of parasitic streaming instabilities and cause the waste of ordered beam energy for ion and electron heating. This heating and anomalous diffusion result in violation of regularity and in failure of the acceleration process. While using beam-plasma collective interactions for acceleration, it is necessary to prevent plasma-beam interactions from their natural development, that is, it is essential to prevent transformation to the turbulent state causing heating and anomalous diffusion of a plasma and to create conditions under which the waves with regular phases and narrow frequency spectra will be excited which are appropriate for regular acceleration. These are the principal problems for plasma acceleration methods. The following problems will, therefore, be discussed in this report: the increase of effectiveness of wave excitation in plasma by intense relativistic and nonrelativistic beams; the interaction of modulated relativistic beams with plasma; the control of high-frequency and low-frequency spectra of excited oscillations. We shall also discuss questions on excitation of single pulses (which are essential for acceleration) in a plasma by means of electrons, and also the problems of electron-beam focusing based on the application of induced radiation.

1 AN INCREASE IN EFFECTIVENESS OF WAVE EXCITATION IN PLASMA BY INTENSE RELATIVISTIC AND NONRELATIVISTIC BEAMS

As has been shown theoretically[6] and experimentally,[7] the fraction of electron beam energy expended on regular wave excitation, that is, the transformation coefficient of electron beam energy into wave energy, equals:

$$\left(\frac{n_b}{n_p}\frac{v_0}{v_q}\right)^{1/3}\gamma \ll 1 \quad \text{for spatial wave rise}$$

and

$$\left(\frac{n_b}{n_p}\right)^{1/3}\gamma \ll 1 \quad \text{for wave rise in time}$$

n_b—beam's density,

n_p—plasma density.

In experimental conditions this value is 10 to 30 per cent. The main reason leading to limitation in amplitude of excited waves is the effect of nonlinear saturation of waves caused by particle trapping

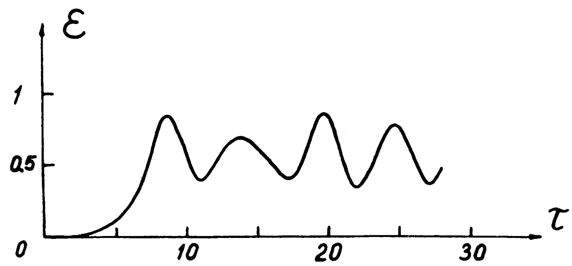

FIGURE 1 Time dependence for the amplitude of the beam-excited monochromatic wave in a plasma.

into the wave potential well and the associated oscillation in amplitude of the electric field strength and frequency.[6] The cause of these oscillations lies in periodic pumping of energy from bunches into which electron beams are divided to a wave, when bunch velocity exceeds the phase velocity and the wave energy absorption—when the bunch velocity becomes less than the phase velocity of a wave (see Figure 1). Dimensionless variables ε, τ are equal, respectively, to

$$\tau = \omega_p t\left(\frac{n_b}{n_p}\right)^{1/3}\frac{1}{\gamma};\ \varepsilon = \frac{E}{\sqrt{4\pi n_b m v_0^2 (n_b/n_p)^{1/3}\gamma}}.$$

Saturation effects can be eliminated and the beam-energy-into-wave transformation coefficient can be substantially increased under conditions when the phase velocity of the excited waves is variable and it decreases in the direction of beam motion in such a way that while the beam is retarded, which is caused by wave excitation, the synchronism between the beam and the wave is maintained.[8] In this case the particles trapped by the wave are grouped in the retarding phase, at which the rate of their motion coincides with the phase velocity of the wave motion, and they continue to release their energy to the wave. It is of prime importance that as a result of beam particle bunching, not only equilibrium particles but also nonequilibrium particles are captured into synchronous motion with the result that maximum energy of the excited oscillations becomes comparable with the beam energy. This effect is essentially caused by the Veksler–McMillan autophasing and is the inverse of autophasing in linear accelerators.

Figure 2 gives the results of the solution for the nonlinear problem of monochromatic wave excitation by the electron beam in a plasma in the case of variable phase velocity under synchronism. A set of equations describing this interaction takes the form:

$$\frac{d\alpha}{d\xi} - \delta + f(\xi) = \int_{-1/2}^{1/2} \cos(2\pi\tau + \alpha)\, d\tau_0$$

$$\frac{d\varepsilon}{d\xi} = \int_{-1/2}^{1/2} \sin(2\pi\tau + \alpha)\, d\tau_0$$

$$\frac{d^2\alpha}{d\xi^2} = \varepsilon \sin \varphi_{0s}$$

$$\frac{d^2\tau}{d\xi^2} = -\frac{1}{2\pi}\varepsilon \sin(2\pi\tau + \alpha)$$

$$n(z) = n_0(1 + \Delta f(z));\ \Delta = \left(\frac{n_b}{n_p}\right)^{1/3}\left(\frac{v_q}{v_0}\right)^{2/3};\ \xi = \frac{kz'}{2\pi}.$$

The change in phase velocity which provides constancy of synchronous phase was reached by changing plasma density. In Figure 2 are shown the results of this problem solution. Dimensionless variables ξ and ε are respectively equal to

$$\xi = \frac{\omega_p z}{v_0}\left(\frac{n_b}{n_p}\frac{v_0}{v_q}\right)^{1/3}\frac{1}{\gamma};$$

$$\varepsilon = \frac{E}{\left[4\pi n_b m v_0^2 \gamma^2\left(\frac{n_b}{n_p}\frac{v_0^4}{v_q^4}\right)^{1/3}\right]^{1/2}}.$$

It follows from Figure 2 that as distinguished from the case with constant phase velocity, the saturation and oscillation of the excited wave amplitude do not occur. The wave amplitude grows monotonically and in the case under consideration the beam energy which transforms into energy of excited oscillations is

$$\left(\frac{v_q}{v_0}\frac{n_b}{n_p}\right)^{1/3}$$

$\sim$1.5 times more than the energy for the constant phase velocity. The motion along the phase plane for the case of variable phase velocity is also shown in Figure 2. While comparing it with the constant phase velocity case one can easily reveal a great difference. In the first case, the bunches produced are oscillating around zero field phase and, therefore, energy exchange between bunches and field does not take place on the average. In case of alternating phase velocity, as one would expect, particle oscillations occur around the synchronous phase, beam particles continuously release their energy to the field, and the bunch shifting down in velocity is constantly retarded. It is of interest to

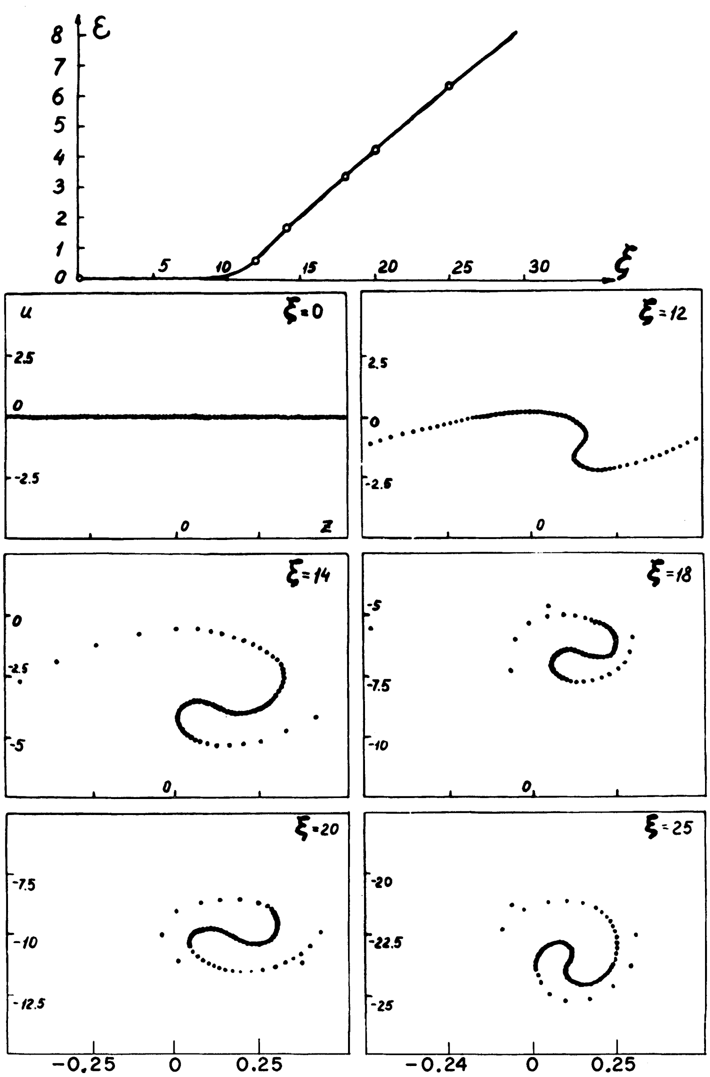

FIGURE 2 Time dependence of the excited wave amplitude and the phase plane of beam particles in the case of a variable phase velocity.

note, that 85 per cent of the particles are concentrated in a bunch. Experimental studies of Berezin, Fainberg *et al.* show the possibility of growth in interaction effectiveness to be a real one at alternating phase velocity. In spite of the fact that changes in plasma density and wave velocity did not follow exactly the above-mentioned law, the decrease in wave phase velocity resulted in growth in interaction effectiveness. Figure 3 shows experimental dependence of excited field amplitude along the plasma-beam interaction region. Curve I (Figure 3) applies to the uniform density case. One can easily see the saturation and subsequent amplitude oscillations caused by particle trapping in a wave field (see also the work of Malmberg and Wharton.[9] Curve II shows dependence of field vs length when the condition of synchronism is approximately fulfilled. As would be expected, in this case the oscillations and saturation effect vanish and the amplitude of excited oscillations increases sharply. Thus one may consider the possibility of substantial increase of excitation effectiveness essential for wave acceleration in synchronous conditions to be proved both theoretically and experimentally.

At the same time we should like to make the following notes. One may expect a short length of

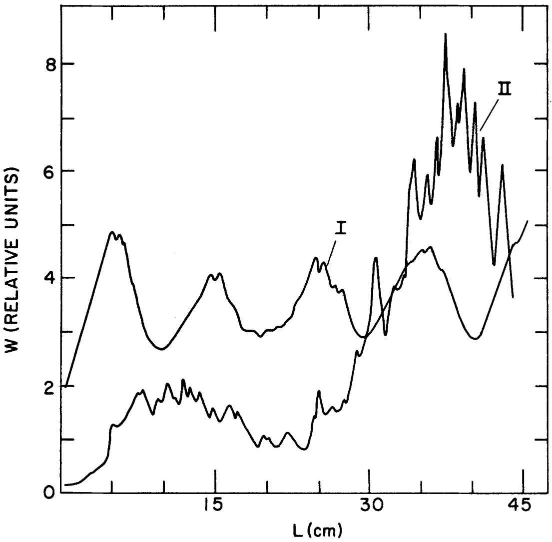

FIGURE 3 Variation of the high frequency electric field intensity over the interaction region of the modulated electron beam with a homogeneous and inhomogeneous plasma. Modulation frequency is 970 kHz, modulating signal power is 0.4 W, beam current is 0.4 A, energy is 8 keV. Curve I—the homogeneous plasma with a density 10^{11} cm^{-3}, Curve II—the inhomogeneous plasma (the plasma density decreases along the beam direction by a factor of 3).

ion acceleration by means of ionization waves in machines of the Blumlein type to be also caused by lack of synchronism and constancy of the rate of motion of the ionization front. The most natural methods of realization of synchronism in this case are the modification of the ionization front rate by creating gas pressure inhomogeneity along the accelerating system. It will be recalled that in the case when ionization is caused by binary collisions, the ionization front velocity is, according to Rostoker, equal to

$$v_\varphi = \frac{c}{\omega_p \tau_N}, \frac{1}{\tau_N = n\langle \sigma v \rangle} \quad \text{(Ref. 10).}$$

In experiments made at the Physical-Technical Institute for testing this possibility a tenfold pressure drop was created and in this case the ionization front velocity was changed over the range 0.8 to 1.6 × 10^{10} cm/sec. It would be expected that with an increase of ionization front velocity over the accelerator, the length of ion acceleration region substantially grows. It should be noted that the results obtained in these experiments are likely to confirm that in plasma generation, when a high-current relativistic beam passes through a gas, collective effects also play their part, that is, ionization by plasma electrons in the electric fields of the beam-excited waves. In this case some new methods arise for controlling the ionization front velocity.

2 INTERACTION OF MODULATED RELATIVISTIC BEAMS WITH A PLASMA

One of the methods of increasing the wave excitation[3] with external microwave sources or some spectra is the use of a preliminary beam modulation [3] with external microwave sources or some passive devices such as ondulators (travelling-wave UHF generators), waveguides with periodic structures or laminar plasma, etc. At first glance it seems that for the ultra-relativistic beam power the modulation required should be very high. However, in practice, this power value is not so large when the use is made of the effect of the initial signal amplification due to the beam interaction with a plasma or waveguide structures. The extreme case of the modulated beam is the periodic bunch sequence. If the conditions of coherence within one bunch and between bunches are satisfied, then the intensity of the oscillations excited by each bunch would be as high as possible. The physical features in the interaction of relativistic, highly modulated beams with a plasma may be studied in experiments with small currents of the order of ~1 A; however, for the case of a high energy of the order of several MeV, when relativistic effects become essential, we studied a highly modulated relativistic electron beam from a linear accelerator of a common type but with an increased current.[11,12] The beam parameters were as follows: the energy—2 to 3 MeV, the pulse current—1 A, the pulse duration—2 μsec, the beam diameter—10 mm, the phase bunch width—60°. The experiments were made with a decaying plasma. The plasma density varied within the range of 10^{14} to 10^{10} cm^{-3}. The bunch length obtained from the linear accelerator was essentially smaller than the wavelength excited in a plasma, and the bunch sequence frequency coincided with an excited oscillation frequency. These two effects provided the conditions for establishing a coherent wave excitation in a plasma by a coherent sequence of relativistic bunches.†

† This coherent wave excitation is the conversion of the V. I. Veksler coherent acceleration effect.

The experimental results are shown in Figures 4, 5 and 6. The energy beam spectra after the plasma interaction are shown in Figure 4. The figure shows that electron energy losses in oscillation excitation are 150 to 200 keV, i.e., 10 per cent, with most electrons being accelerated up to 100 keV. maximum losses are observed in the case of coherence between bunches, when $\omega_p = \omega_{mod}$, which corresponded to the density 10^{11} cm^{-3} in our experiments. It is seen from Figure 5 that the spectra of excited oscillations are rather narrow. In the experimental conditions the losses of a single

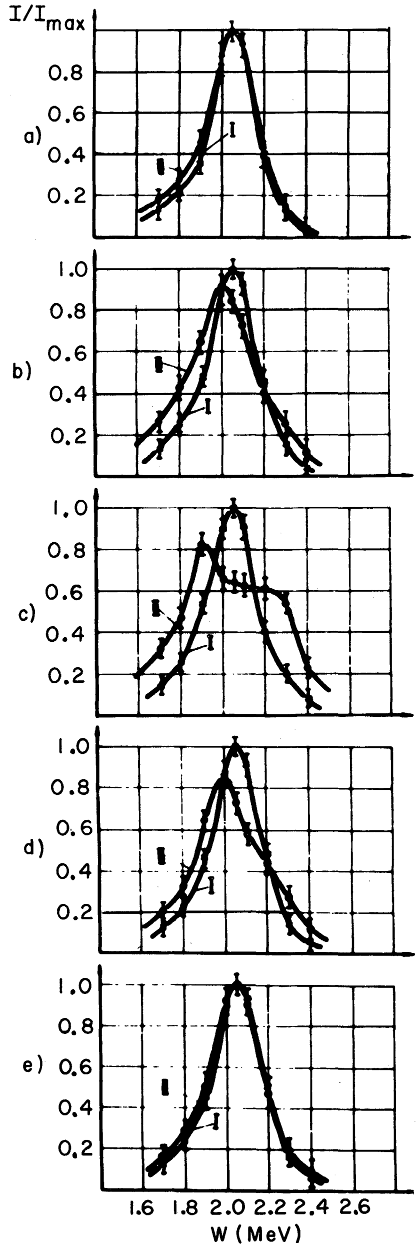

FIGURE 4 Energy spectra of electrons for the beam current 1 A. Curve I—without plasma, Curve II—with plasma.

a — $n_p = 5 \times 10^{12}$ cm^{-3}; b — $n_p = 10^{12}$ cm^{-3}; c — $n_p = 10^{11}$ cm^{-3}; d — $n_p = 5 \times 10^{10}$ cm^{-3}; e — $n_p = 10^{11}$ cm^{-3}.

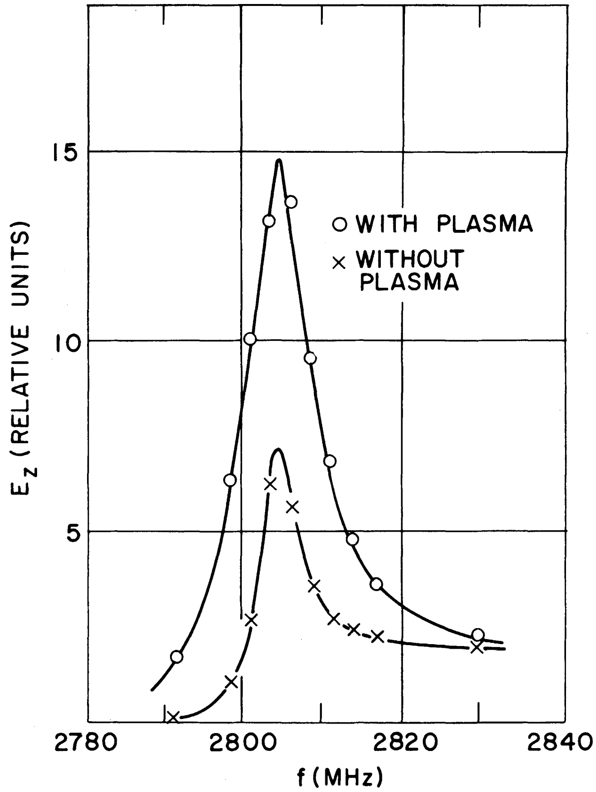

FIGURE 5 Frequency spectra of the E_z-field component. o—with plasma, x—without plasma, $n_p = 10^{11}$ cm^{-3}.

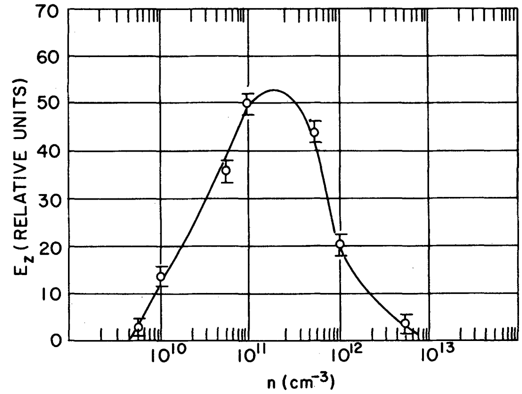

FIGURE 6 The E_z-field amplitude as a function of the plasma density.

particle are 10^{-9} eV/cm. These losses make 600 eV/cm with account for the coherence in a bunch within the interaction length, and they are 12 keV with account for the coherence between bunches (20 bunches over the interaction length) and 600 keV with account for the storage effect (2000 bunches). The difference between theoretical and experimental losses is explained by a plasma inhomogeneity. With homogeneity improvement by 60 per cent, the losses increased by 15 per cent. Thus, these experiments revealed the coherent losses by a highly modulated electron beam for the excitation of plasma oscillations. Despite small currents, due to coherence effects the relative losses are comparable and they even exceed those by high-current nonmodulated relativistic beams. The use of modulated relativistic beams makes it possible to excite oscillations with narrow frequency spectra.

With the increase of electron beam intensity the difficulties in modulating such beams also increase. Therefore, in this respect the automodulation of high-current relativistic beams seems very promising. The latter occurs, in particular, in the interaction with a plasma-filled waveguide periodic structure. The generation in such systems is known to be realized by Nation.[13]

To get the automodulation effects in our experiments (Tkatch, Fainberg, *et al.*[14]), where the beam current was 60 kA and electron energy was 0.8 to 1 MeV, we used the ready-made accelerating structure of the linear accelerator. At pressures 0.1 to 1 mm Hg on its way through the section the beam created a plasma with a density of 10^{12} to 10^{13} cm which resulted in the deceleration decrease down to 0.4 to 0.6 β in the section. Though the conditions of the spatial and time resonances were not fulfilled (the beam velocity differed from that of the wave and the plasma resonance frequency differed from the waveguide frequency) the automodulation was followed by 10 to 15 MW very high frequency power generation with a maximum at the frequency of 2600 MHz. The electron beam thus modulated may be expected to interact effectively with a plasma after it leaves the waveguide.

The analysis of the experiments on the interaction of relativistic beams with a plasma made in our laboratory and others shows that they use and study somewhat insufficiently the effects related with relativity, i.e., the effects which depend on the energy rather than on the velocity of the beam, as well as the effects related with the wave propagation peculiarities, where the phase velocity approaches c. Since with the relativistic mass increase the amplitude and the oscillation frequency of plasma and beam electrons decrease and hence, the corresponding values ρ_r and v_r also decrease, then in using relativistic beam instabilities it is necessary to search for radiation mechanisms in which the radiation intensity of individual particles increases in proportion to γ^2. In this case the total radiation intensity may be expected not to decrease but to increase. It is known that in a circular motion or any other nonlinear motion the radiation intensity of a single particle increases greatly in the ultrarelativistic case. For a linear motion there are also a number of effects which determine the increase of the radiation intensity of a single particle. This is, first of all, the effect of electromagnetic wave reflection from relativistic beams moving in vacuum or a plasma (Landecker,[15] Fainberg, Tkalich, Lampert,[16] etc.). These effects are known to be based on the frequency and amplitude multiplication when electromagnetic waves are reflected by a moving mirror which was predicted by Einstein. Due to the double Doppler effect the amplitude and frequency of reflected waves increase by a factor of $(1 - \beta^2)^{-1}$. In the case when the beam moves through the plasma these effects may be observed at nonrelativistic beam energies as well. They have been observed experimentally at PhTI (Kharkov).

3 FLOW INSTABILITY CONTROL

Preliminary beam modulation is not only the way to increase the efficiency of the beam interaction with a plasma but it also can be used to control flow instabilities[3] which are the main obstacles in the realization of plasma acceleration methods, since the instabilities lead to plasma heating and anomalous diffusion and to the excitation of wide wave packets of low frequency and high frequency waves. The investigation of the nonlinear stage of control processes reduces to the consideration of two nonlinear perturbations interacting in the beam-plasma system. In this case it is assumed that the modulation amplitude at the system exceeds essentially the fluctuation amplitude and the modulation frequency coincides with the resonance plasma frequency. The equation system describing this interaction has the form[17]

$$v_q \frac{dE_j}{dz} = \frac{4\pi e n_b v_0}{T} \int_{-T/2}^{T/2} \sin[\alpha_j(z) - \omega t'(z, t(0))]\, dt(0)$$

$$v_q\left[\frac{d\alpha_j}{dz} - j\frac{\omega - \omega_0}{v_q}\right]E_j = \frac{4\pi e n_b v_0}{T} \int_{-T/2}^{T/2} \cos[\alpha_j(z) - \omega t'(z, t(0))]\, dt(0).$$

Here $t' = t - (z/v_0)$, $t(0)$ is the time of particle entry into the plasma, the particles being at a point z at the moment t, T is the total perturbation period (it is assumed that perturbation frequencies may be represented as $\omega_0 = 2\pi m/T$, $\omega = 2\pi n/T$, m and n being the integers). In deriving these equations we neglected small values of

$$\frac{v'}{v} \sim \frac{\kappa v_0}{\omega} \ll 1$$

(v' is the oscillation velocity of the beam particles). With the same accuracy the equation of the beam particle motion may be written as

$$\frac{d^2 t'}{dz^2} = -\frac{e}{m v_0^3} \sum_{j=-N}^{N} E_j \sin[\alpha_j - \omega t'].$$

These equations describe the spatial enhancement of the packet of $(2N + 1)$ unstable oscillations for a stationary electron beam injection into plasma. In terms of dimensionless variables we have

$$\xi = \frac{\omega_p z}{v_0}\left(\frac{n_b}{n_p}\frac{v_0}{v_q}\right)^{1/3}, \quad \tau = -\frac{t'}{T}, \quad t_0 = -\frac{t(0)}{T}$$

$$\delta = \frac{\omega - \omega_0}{\omega_0\left(\dfrac{n_b}{n_p}\dfrac{v_q^2}{v_0^2}\right)^{1/3}}, \quad \nu = 2\pi m\frac{d\tau}{d\xi} = \frac{v - v_0}{v_0\left(\dfrac{n_b}{n_p}\dfrac{v_0}{v_q}\right)^{1/3}}.$$

The system of these equations reduces to the universal one with a replacement of the dimensionless time and the coordinate $\tau \to \xi$. The dimensionless units for the electric field are determined from the conditions of trapping the beam particles in nonlinear operating conditions (i.e., at $\varepsilon_j \sim 1$) into the potential wells created by excited waves. In this case

$$\sqrt{\frac{e\varphi_0}{m}} \sim \left|v_0 - \frac{\omega}{k}\right| \sim v_0\frac{\kappa}{k}.$$

The energy of beam-excited oscillations in the stationary problem is

$$\sum \frac{|E_k|^2}{4\pi} \approx n_b m v_0^2 \left(\frac{n_b}{n_p}\frac{v_0}{v_q}\right)^{1/3} \frac{v_0}{v_q} \sum \varepsilon_j^2.$$

The factor v_0/v_q in this form shows the possibility of oscillation storage in the beam injection into plasma due to which at $v_q \ll v_0$ the energy density of oscillations may exceed considerably the energy density in the beam.[8] We present the solution of these equations for the case when due to the modulation the initial amplitude of the fundamental wave $\varepsilon_{\omega_0}(0)$ exceeds essentially those of probe waves. The probe waves arise as a result of thermal fluctuations in a plasma and for them

$$\varepsilon(0) \sim \left(\frac{\omega_p^3}{n_b v_0^3}\frac{v_q}{v_0}\right)^{1/2} \sim 10^{-3} - 10^{-4}.$$

Figures 7a and 7b show nonlinear dynamics of three unstable perturbations for the case when the initial amplitude of the fundamental wave exceeds those of probe waves only by one order of magnitude. Under these conditions at any mistuning value there is an excitation of the monochromatic wave with the frequency equal to a modulation frequency. The wave initiates the beam splitting into bunches of trapped particles rotating synchronously on the phase plane. The probe perturbations are suppressed in this case. For comparison in the same figures the dashed line shows the growth of probe waves in the absence of the fundamental wave. Only at rather large distances from the beam entry into plasma $l_0 \sim (20\text{–}30)\ 1/\kappa$ the monochromatic wave instability becomes inevitable and the excitation of slow satellites occurs. At large differences between amplitudes of the fundamental and probe waves the distance, over which the beam-excited wave remains monochromatic, may be increased considerably (in Figures 7c and 7d for $\varepsilon_{\omega_0}(0) = 10^{-2}$, $\varepsilon_{2\omega_0 - \omega} = 10^{-4}$ the distance $l \sim (30\text{–}40)\ 1/\kappa$.

The results obtained confirm the possibility of controlling the spectrum of beam-excited oscillations in a plasma with a preliminary (beam) modulation of oscillations of a rather small amplitude.

Berezin, Fainberg *et al.* investigated experimentally the nonlinear stage of control processes. The results obtained are shown in Figures 8 and 9. The main result is the total suppression of other harmonics by a main mode. Frequencies and amplitudes of field oscillations measured· experi-

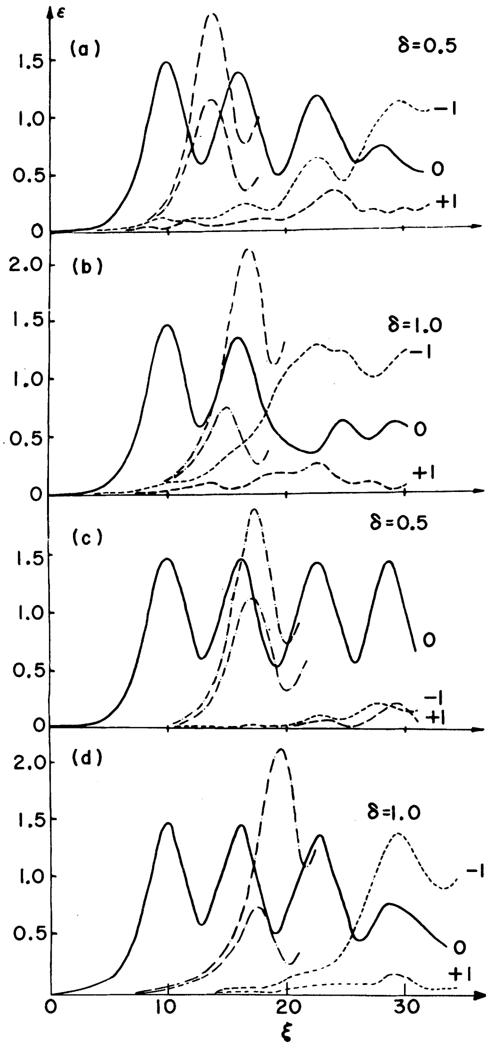

FIGURE 7 Nonlinear dynamics of three-frequency unstable perturbations in the plasma-beam system.

mentally and determined theoretically are in good agreement.

4 LOW-FREQUENCY INSTABILITY CONTROL

Plasma ion heating and anomalous diffusion are determined by low frequency oscillations which are not excited directly by an electron beam in the experiments studying plasma acceleration methods, but arise as a result of a nonlinear interaction of very high frequency oscillations. Kornilov, Krivoruchko *et al.*[18] have shown that this transformation occurs very effectively: up to 30 per cent

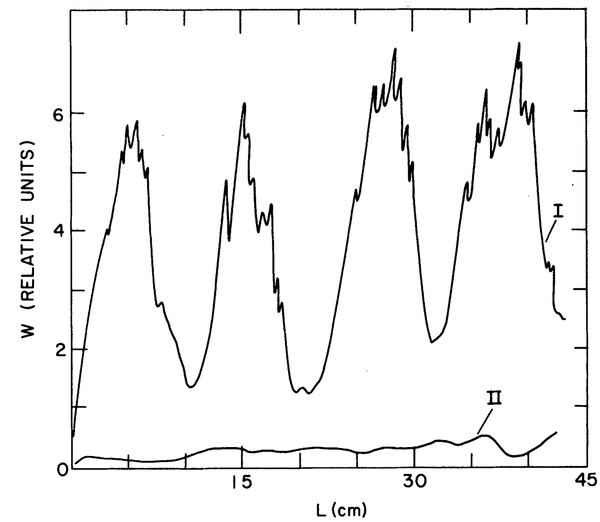

FIGURE 8 Variation of the very high frequency electric field intensity along the interaction region of the modulated electron beam with a plasma. Modulation frequency—970 MHz, modulating signal power—0.4 W. Curve I—oscillation frequency 970 MHz, Curve II—oscillation frequency 1100 MHz. For Curve II the scale along the y-axis is $\times\ 10^{-1}$.

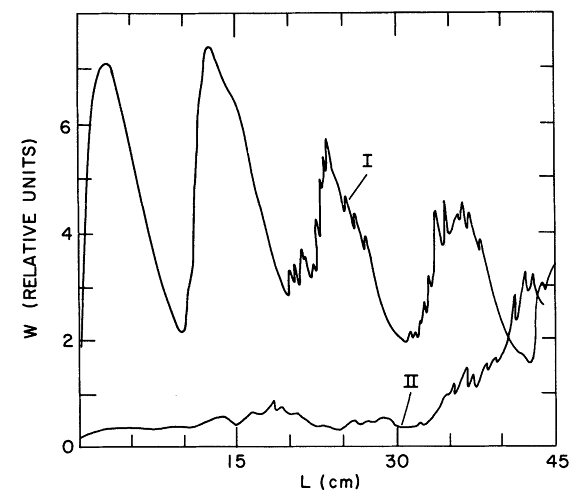

FIGURE 9 The same as in Figure 8 but for the case of a two-frequency electron beam modulation. Modulation frequencies are 970 and 1100 MHz, the modulating signal powers are 0.4 and 0.01 W, respectively. Curve I—the oscillation frequency is 970 MHz, Curve II—the oscillation frequency is 1100 MHz.

of the very high frequency oscillation energy may be transformed into low frequency oscillations. These effects which are deleterious to the acceleration processes are eliminated by narrowing the very high frequency oscillation spectrum and by controlling the low frequency oscillation spectra. Since in the experiments considered the oscillations were identified which are responsible for ion heating and plasma anomalous diffusion, it is possible to compare these acceleration hindering processes by controlling low frequency oscillation spectra.

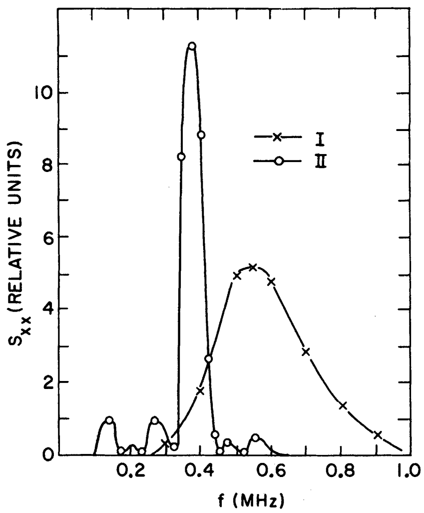

FIGURE 10 A frequency spectrum of oscillations generated in a plasma-beam discharge without electron beam modulation (Curve I) and with electron beam modulation (Curve II). Beam current—4 A, energy—10 keV, modulation frequency—500 kHz.

Figures 10, 11 and 12 show the low frequency spectra controlled by a direct modulation of low frequency oscillations (Berezina *et al.*)[19] (Figure 10), as well as by a multifrequency very high frequency modulation[18] (Figures 11 and 12). These figures show that the two methods lead to the effective low frequency spectrum control and make it possible to suppress the wave excitation resulting in plasma heating and anomalous diffusion. When plasma electrons are accelerated by external electric fields in the devices of the linear plasma betatron type a great danger lies in the excitation of ion-acoustic or Budker–Bunemann oscillations which absorb the energy of the ordered electron motion. Therefore the problem of control and suppression of these instabilities is of great importance for creating powerful sources of electrons with long pulse duration. An effective method to suppress these instabilities is that using the plasma inhomogeneity (the author,[3] Ryutov,[20] Bers[21]). This method was able to suppress instabilities in a linear plasma betatron[22] with a current of 10 kA, electron energy of 200 keV, and a pulse duration of 0.7 μsec, where

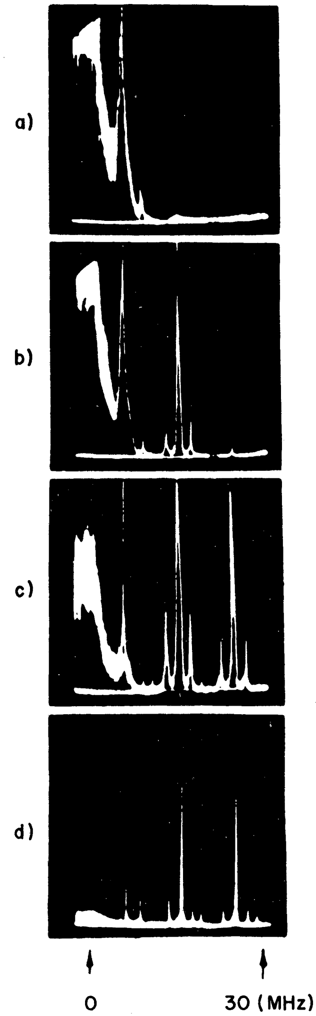

FIGURE 11 Suppression of drift wave spectrum for multifrequency modulation.

an excited oscillation power of 10 to 15 MW (of radiated power) was obtained. Another method of suppressing ion-sonic instabilities also is of interest. It was suggested together with Buts and is based on using a two-component ion plasma.

5 ACCELERATION OF SINGLE PULSES

One of the important problems in new methods of acceleration is the localization of accelerating fields along the accelerator and in the radial direction, since in this case high intensities of accelerating fields can be obtained for reasonable values of very high frequency fluxes and electromagnetic energy density, and also of losses due to

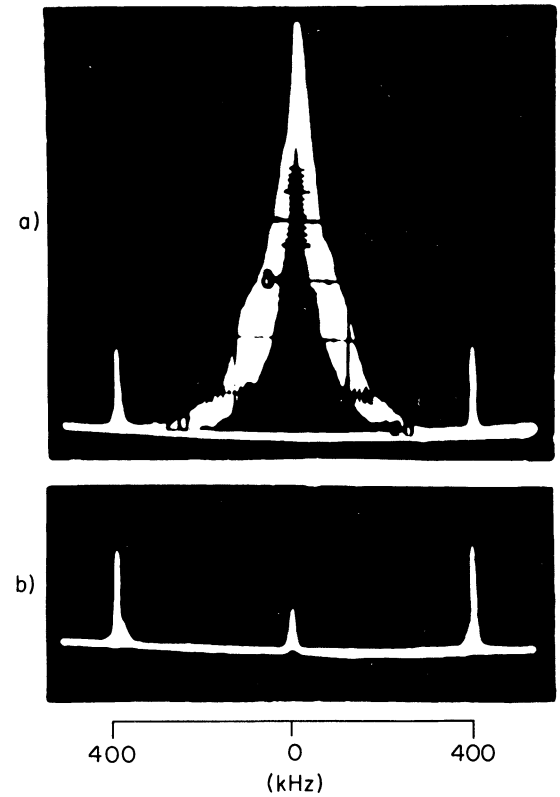

FIGURE 12 Suppression of drift waves by an external electric field in the beam-plasma system.

the energy dissipation in the accelerating systems of the power supply which excites these waves (electron beams, external generators). The most effective method of the longitudinal energy localization is the use of single pulses moving in a plasma and noncompensated electron beams. This possibility was shown by the author in Ref. 2. Reference 23 shows the possibility of forming a single wave in an E-layer. Here, the electric field intensity proves to be

$$E \sim \sqrt{8\pi n_0 \varepsilon_b \frac{\omega_H}{\omega_0}(1 - \beta^2{}_\varphi)}$$

and the pulse length is

$$l \sim \frac{c\omega_H^{1/2}}{\omega_0^{3/2}}(1 - \beta_\varphi^2)^{1/2}.$$

The field localization in a very limited region along the acceleration direction by using single pulses in a plasma eliminates one of the essential advantages of vacuum acceleration methods where a strong localization is observed in the region of electron bunches or rings. It is very essential that while for the localization under vacuum conditions external fields are required as the equilibrium in them is of a statistical character, in fact, in the case of pulses in a plasma there is a dynamic equilibrium. The prospects of acceleration by solitary waves are discussed in detail in the Dubna Symposium report by M. S. Rabinovich and V. N. Tsytovich. We shall note here only one problem which is important in developing the acceleration methods using single pulses, and the problem of excitation and acceleration of these pulses.

One of the methods of solving this problem is the pulse acceleration by electron beams. Studying a Langmuir solution in a bound plasma which is in a high magnetic field. Shapiro and Shevchenko have shown that using the electron beam one can obtain the effective amplification of the soliton's amplitude and its acceleration until the soliton's velocity exceeds the beam velocity. It should be noted that this rather nontrivial fact of the possibility of Langmuir soliton existence in a bound plasma was shown by Rutkevich[24] and Ikezi *et al.*[25] The maximum value for the amplitude of the beam accelerated soliton was found to be

$$\varphi_0^{\max} = \frac{mv_\varphi^2}{e}\Delta \lesssim \frac{3\pi}{4}\sqrt{\frac{mv_\varphi^2}{e}\varphi_0(0)}$$

$$\Delta = \frac{3\pi}{4}\frac{v_0 - v_\varphi(0)}{v_\varphi(0)}.$$

6 POSSIBILITY OF USING INDUCED RADIATION FOR ELECTRON BEAM FOCUSING

For the effective interaction of high energy relativistic and nonrelativistic electron beams with a plasma, there should be a strong radial beam focusing with a low velocity spread. The most natural possibility, shown long ago by Budker, lies in using the effects of noncoherent spontaneous radiation. The radiation initiates dissipation in the system, it ceases to be Hamiltonian and Liouville's theorem is no longer valid for it. Hence the phase volume may now be decreased and the radial focusing is not accompanied by the velocity spread. Since in this method a noncoherent spontaneous radiation is considered this leads to a long time for electron-beam relaxation. Therefore, this method may be applied only for cyclic devices. To increase the effects of radial focusing it is natural to use an induced coherent or noncoherent radiation. This idea was put forward independently by the author and Yarkovoy. The relevant calculations made in Ref. 26 have shown that with this method one can obtain an essential efficiency increase in the radial focusing of charged particles. Here the case of surface waves was considered. The efficiency may also be increased with the waves radiated from the system, as here an intense recoil pulse arises in the radial direction.

We have considered some ways of increasing the efficiency of methods of charged particle acceleration in a plasma. The experiments made up to date are in full agreement with the theory and they offer encouragement for the successful development of methods for charged particle acceleration in a plasma based on wave excitation by powerful relativistic and nonrelativistic electron beams.

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